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A search for extragalactic H_2O maser emission towards IRAS galaxies II – Discovery of an H_2O maser in the Seyfert 1 galaxy NGC 4051

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ABSTRACT

Water vapor maser emission in the 6_{16}–5_{23} transition towards the narrow-line Seyfert 1 (NLS1) galaxy NGC 4051 has been discovered during an ongoing single-dish extragalactic water maser survey. The Doppler-shifted maser components appear to bracket maser components lying near the systemic velocity of the galaxy symmetrically. The tentative result of a Very Large Array (VLA) snapshot observation is that the masers are confined within 0.1 arcsec (5 pc at a distance D = 9.7 Mpc) of the radio continuum peak seen at 8.4 GHz. The low luminosity of the maser ($\sim$ 2 $L_\odot$) is not typical for masers that coincide with the radio continuum nucleus and appear associated with Active Galactic Nucleus (AGN) activity. A low-luminosity maser in a Type 1 Seyfert nucleus could be explained by a low maser gain resulting from the lower inclination of an obscuring disk around an active nucleus.

Key words: galaxies: Seyfert – galaxies: active – galaxies: individual(NGC 4051): radio lines

1 INTRODUCTION

The existence of super massive black holes in active galactic nuclei (AGN) was clearly proved by the detection of a thin Keplerian rotating disk in the LINER galaxy NGC 4258 that was imaged using strong H_2O maser emission (Miyoshi et al. 1995). VLBI observations have shown that these masers are distributed in the thin disk with a radius of 0.13 – 0.26 pc tracing a region down to $\sim$ 40,000 Schwarzschild radii, which is the lowest radial distance ever imaged in the 'central engine' of an AGN (Herrnstein et al. 1996). Motivated by this discovery, a number of single-dish surveys for new water masers in AGN have been carried out (e.g., Braatz, Wilson & Henkel 1996) and have yielded a catalogue of about 30 sources in early 2003 (Greenhill et al. 2003). Studies of several H_2O masers at milliarcsecond resolution using VLBI have shown that the masers do not always lie around an active nucleus (Moran et al. 1999), but that some of them are associated with other AGN activities such as jets or nuclear outflows. H_2O masers are found to be important tools for investigating the nuclear kinematics in various types of active galaxies, in particular narrow-line AGN. A number of broad-line AGN have been surveyed for masers, however, no water maser emission has yet been detected in broad-line Seyfert 1 galaxies. In 2001, we began a survey program searching for H_2O masers in far-infrared (FIR) luminous galaxies (Hagiwara, Diamond & Miyoshi 2002, hereafter Paper I). In Paper I we reported the first confirmed detection of a maser in the Seyfert galaxy NGC 6240. The aim of this survey was to find new H_2O masers in 'radio-excess' FIR luminous galaxies, which were selected on the basis of a large ratio of the correlated flux density at 21-cm (using the VLA at $2-25$ arcsec resolution) to the FIR flux density. Details on the sample selection were described in Paper I. The new detection in NGC 6240 motivated us to continue the survey of the 'radio-excess' FIR galaxies.

In this letter, we briefly summarize the results of the ongoing maser survey following Paper I, which has culminated in the discovery of a water maser in the Type 1 Seyfert galaxy NGC 4051. In addition, we present preliminary results from VLA snapshot observations of this maser.

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2 THE SURVEY

Survey observations of H_2O emission in the 6_{16}-5_{23} transition at 22.23508 GHz have been carried out with the MPIfR 100-m radio telescope at Effelsberg in March and September 2002. Throughout the survey, a K-band HEMT receiver with two orthogonal linear polarizations was used with a system temperature of 70–120 K depending on atmospheric conditions. The spectrometer was an 8-channel digital autocorrelator (AK 90), each channel having a bandwidth of 40 MHz ($\sim$ 540 km s^{-1}) and 512 spectral points (velocity resolution $\sim$ 1.1 km s^{-1}). Four channels were employed for each polarization. The centre spectral points of each correlator were offset from the systemic velocity of the galaxies by typically $\pm$ (20 – 30) MHz, thereby providing a total bandwidth of 100 – 130 MHz per polarization. More details on the observations can be found in Paper I.

3 SURVEY RESULTS

A total of 24 galaxies from the FIR galaxy sample have been observed, including previously observed objects in this survey. Ten newly observed galaxies are listed in Table 1. During the survey, we discovered a new water maser toward a narrow-line Seyfert 1 (NLS1) galaxy NGC 4051 (Osterbrock & Pogge 1985) on 5 March 2002. The detection was confirmed six months later on 14 September. The parameters of the galaxy are summarized in Table 2, where the systemic velocity of the galaxy ($V_{\rm LSR}$ = 730 $\pm$ 5 km s^{-1}) is adopted. The sample of 24 selected galaxies consists of Type 1 and 2 Seyferts, compact HII nuclei and LINERs. The two new detections in NGC 6240 and NGC 4051 suggest an $\sim$ 8% detection rate, which is greater than that of $\sim$ 3% in Braatz, Wilson & Henkel (1996) and that of $\sim$ 4% in Greenhill et al. (2003), all of which are based on modest number statistics. While the galaxies surveyed in Braatz, Wilson & Henkel (1996) and Greenhill et al. (2003) were selected from a distance-limited AGN sample with systemic velocities $\lesssim$ 8000 km s^{-1}, we constructed a radio-excess FIR galaxy sample based on the radio and FIR properties of the AGN. The total number of radio-excess FIR galaxies is about 30, of which at present eight galaxies contain water masers. These results suggest that the presence of the H_2O masers in active galaxies correlates well with the combined presence of a considerable FIR flux density (at 60 μm and 100 μm) and a radio compact core originating in the dust heated by an active nucleus or a compact HII region (Baan 1997).

The detection of an H_2O water maser in Type 1 Seyfert galaxies is still rather unique since most of the extragalactic H_2O masers have been found in Type 2 Seyferts or LINERs. Since the Seyfert galaxy NGC 5506, which contains an H_2O maser, has recently been re-classified as a NLS1, NGC 4051 is the second detection in this type of galaxy (Nagar et al. 2002). Figure 1 shows the spectrum of the maser in NGC 4051 observed at two epochs 6 months apart. The emission is dominated by narrow components with linewidths of $\sim$ 1 – 2 km s^{-1}. Several components in the range $V_{\rm LSR}$ = $\sim$ 670 – 690 km s^{-1} and at $V_{\rm LSR}$ = 712 km s^{-1} varied by a factor of two over six months. The spectrum in Figure 1 shows that several Doppler-shifted maser components are seen on either side of the systemic velocity. Their centroid velocities are listed in Table 3.

A first interpretation is that the maser components are distributed quasi-symmetrically relative to the 730 km s^{-1} component at the systemic velocity. The discovery spectrum also displays a high-velocity component at $V_{\rm LSR}$ = 936 km s^{-1} ($\sim$ 3 σ level), but this component does not have any blue-shifted counterparts. The maser components are observed from 659 km s^{-1} to the weaker component at 773 km s^{-1}, which accounts for a velocity extreme of $\pm$ 70 km s^{-1} relative to the systemic velocity. While these extrema are not as large as the maximum rotation velocity of $\approx$ 1100 km s^{-1} for NGC 4258 (e.g., Miyoshi et al. 1995), such symmetrically or quasi-symmetrically distributed emission has not been observed except in the cases of NGC 4258, NGC 1068 and NGC 2960 (Greenhill et al. 1996; Henkel et al. 2002). We searched for additional components within $\pm$ 1000 km s^{-1} of the systemic velocity, but none were detected at the 3 σ sensitivity levels of 15 – 45 mJy, depending on the velocity range (Table 1). No acceleration of the maser components was detected over the six months interval, yielding an upper limit for the drift rate of $\sim$ 2.2 km s^{-1} year^{-1}. The total maser luminosity, assuming isotropic radiation of the emission, is $\approx$ 2 $L_\odot$. The galaxy has been searched for water masers at least twice, in 1983 (Claussen, Heiligman & Lo 1984) and 1995 (Braatz, Wilson & Henkel 1996), with a 3 σ detection level of 130 – 180 mJy. These observations were not sensitive enough to be able to detect even the strongest maser component of $\sim$ 90 mJy shown in Figure 1. Therefore, it is uncertain whether the detected components represent a flaring state for the galaxy. However, the galaxy could be a promising object for study of a 'classical' accretion disk around an active nucleus if the maser components are indeed associated with AGN activity.

4 VLA OBSERVATION OF NGC 4051

On 26 April 2002, a snapshot observation was made with the NRAO [1] Very Large Array (VLA) in A configuration to determine the positions and spatial distribution of the H_2O masers in NGC 4051. We employed two 6.25 MHz IFs, corresponding to a velocity coverage of 84 km s^{-1}, that were centered on $V_{\rm LSR}$ = 680 km s^{-1} and 730 km s^{-1} to cover all known velocity components in the range $V_{\rm LSR}$ = 645 – 770 km s^{-1}. Each IF was divided into 64 spectral channels, yielding a velocity resolution of 1.3 km s^{-1}. The observation was made in phase-referencing mode using a nearby phase-calibrator J 1153+495. 3C 286 was used for amplitude and bandpass calibration. The duration of the observation was 2 hours, resulting in an rms noise of 0.4 mJy beam^{-1}per spectral channel after smoothing the channel spacing to 2.6 km s^{-1}. The uniformly weighted synthesized beam (FWHM) was 0.12 arcsec $\times$ 0.076 arcsec (P.A. = 73°). No continuum emission was detected in this observation to a 3 σ level of $\sim$ 0.3 mJy beam^{-1}. Several velocity components were tentatively detected at or less than the 3 σ detection level. The

[1] The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Table 1. List of galaxies observed with the Effelsberg 100m telescope during 2002. The coordinates of each source are from the NED database.

Source	α (B1950)	δ (B1950)	V_{sys}[a] (km s^{-1})	ΔV[b] (km s^{-1})	Rms noise (mJy)	Epoch[c]
NGC 3227	$10^h\ 20^m\ 43^s$	$+20°\ 09'\ 06''$	1157	260 – 1960	10	A
NGC 3367	10 43 56	+14 00 51	3037	2100 – 3700	10	A
NGC 4051	12 00 36	+44 48 35	730	200 – 1550	5	A
	12 00 36	+44 48 35	730	-300 – 1800	15	B
IRAS 12112+0305	12 11 12	+03 05 20	21980	21070 – 22370	12	A
NGC 4418	12 24 20	-00 36 09	2179	1550 – 2860	20	A
NGC 4594	12 37 23	-11 20 55	1091	490 – 1770	15	A
IC 883	13 18 17	+34 24 05	7000	6260 – 7570	12	A
NGC 5256	13 36 14	+48 31 45	8211	7400 – 9120	10	B
PKS1345+12	13 45 06	+12 32 20	36575	35900 – 37180	10	A
ZW 49.057	15 10 45	+07 24 37	3897	3280 – 4980	13	A

[a] Primarily from NED database
[b] Observed velocity range
[c] Observing epoch; A(4–6 March), B(14–15 September), both in 2002

Table 2. Properties of NGC 4051. Velocity adopted from de Vaucouleurs et al. (1991) is converted to heliocentric systemic velocity using the radio definition. Optical inclination and the distance come from Adams (1977). The radio flux density at 21-cm was measured by the VLA in A configuration (Ulvestad & Wilson 1984). Far-infrared flux densities and luminosity are from the NED data base and Condon et al. (1990). The X-ray luminosity is from Collinge et al. (2001). We assume that H_0 = 75 km s^{-1} Mpc $^{-1}$.

Systemic Velocity (21-cm HI)	723 ± 5 km s^{-1} (Heliocentric)
	730 ± 5 km s^{-1} (LSR)
(optical)	686 ± 13 km s^{-1}
Distance	9.7 Mpc
Inclination (optical)	40°
Optical class	Seyfert 1
F_ν (20-cm)	19 ± 1.5 mJy
F_ν (100-µm)	23.9 ± 0.1 Jy
F_ν (60-µm)	10.4 ± 0.1 Jy
F_ν (25-µm)	2.2 ± 0.1 Jy
L_{FIR} (40 – 120 µm)	$10^{9.57}$ $L_\odot$
L_{Xray} (2 – 10 keV)	(2.3–5.7) 10^{41} erg s^{-1}

positions of most of these components were found to lie in a $\sim$ 0.04 arcsec region centered on Right Ascension (J2000) = $12^h03^m09^s.61$, Declination (J2000)= $+44°31'52''.6$. The components peaking at V_{LSR} = 712 km s^{-1} and 740 km s^{-1} were detected at the $\sim 3\ \sigma$ level, both components were unresolved by the VLA beam. Their beam-deconvolved sizes are typically $\sim$ 60 mas × 40 mas, corresponding to $\sim$ 3 pc × 2 pc in linear scale. Other velocity components were marginally detected with 2 – 2.5 σ levels, but we will not discuss the detection of these components. Further sensitive observations are necessary to measure the precise positions of all the components mentioned above.

5 THE H_2O MASER IN NGC 4051

The position of the radio continuum emission at 8.4 GHz (R.A.(J2000) = $12^h03^m09^s.605$, Dec.(J2000) = $+44°31'52''.73$) was measured with 0.3 arcsec resolution of the VLA in A-configuration (Kukula et al. 1995). The astrometric accuracy of this position was estimated to be between 0.01 and 0.05 arcsec in Kukula et al. (1995). Assuming that the frequency dependence of the radio continuum position is negligible, the position of the masers is coincident with that of the continuum emission within astrometric uncertainties of $\approx$ 0.1 arcsec, or 5 pc at the adopted distance of 9.7 Mpc. The tentatively detected maser components therefore lie in the vicinity of the radio nucleus of NGC 4051. There is also a suggestion of weaker components with a small spatial offset from the radio continuum peak, but this needs to be confirmed.

A question remains as to the true origin of the maser in NGC 4051. Is it associated with a star-forming region or AGN activity? The presence of the marginally detected high-velocity component, which is red-shifted by $\approx$ 200 km s^{-1}, hints that the origin of the maser is AGN activity. The most important point of our discovery is that the maser lies in a Type 1 Seyfert nucleus. NLS1 galaxies exhibit broad-line optical emission, characteristic of Type 1 Seyfert nuclei, together with narrow-line emission; except that these broad-line widths are much narrower ($<$ 2000 km s^{-1}) than in typical Type 1 nuclei (e.g., Osterbrock & Pogge 1985). Observers are likely to look at only a part of the Broad Line Region (BLR) in the nucleus of such galaxies. It has been argued that low-luminosity ($L_{H_2O} \lesssim 10\ L_\odot$) masers are apt to be found outside of active nuclei (Claussen & Lo 1986) but the origin of such a maser in a Type 1 Seyfert nucleus may require a different explanation.

6 INTERPRETATION OF THE LOW-LUMINOSITY

The low-luminosity ($\approx 2\ L_\odot$) of the 'nuclear' water maser and the modest Doppler shifts of any maser components in the nucleus of NGC 4051 can be explained by a lower inclination angle of the disk or disk-like configuration in a heavily obscured circumnuclear medium along our line of sight

Table 3. List of velocities (peak velocities in the flux density) of each maser component close to the systemic velocity obtained from Fig 1. Uncertainties of velocities are 0.5 – 1.1 km s^{-1}. The errors of the flux density are typically 10 percent.

MAR 4-5		SEP 14-15	
$V_{\rm LSR}$ (km s^{-1})	Flux density (mJy)	$V_{\rm LSR}$ (km s^{-1})	Flux density (mJy)
659	15		
664	15	664	30
674	43	674	32
679	54	679	44
683	70		
696	9		
701	17		
712	38	712	85
730	19	730	24
738	43		
741	86	741	85
773	20		
936	14		

(LOS) (Christopoulou et al. 1997). This configuration could significantly decrease the maser gain along the LOS, which results in a lower maser luminosity, as compared with the extragalactic water masers with $L_{H_2O} > 100\ L_\odot$ associated with a highly inclined disk plane. Peterson et al. (2000) argued that the Balmer lines in NGC 4051 might arise in a low-inclination disk-like configuration with an inclination similar to the 40° of the galaxy as a whole, which we would preferentially observe on the near side. They also found that the narrow-line objects could be located at the same position as the AGN BLR. This implies that the H_2O emitting medium would coincide with the structure that obscures the BLR. The putative lower disk-inclination model is consistent with the observed smaller LOS velocities ($v_{\rm los} = v_{\rm rad}\ \sin i$, i = disk inclination angle) of the high-velocity components in a disk. The lower galactic disk inclination (30°– 40°) in NGC 4051 would reduce the apparent LOS velocities by about 40 – 50 per cent as compared to those in a more edge-on disk ($i >$ 70°).

The galaxy shows strong and rapid X-ray variations (Lawrence et al. 1987) but there is no direct evidence yet for strong maser variability. There is no prominent starburst region in the galaxy and the total galaxy mass-to-FIR luminosity ratio is 10^3 times less than that of typical Galactic starforming regions like W 51 (Smith et al. 1983), which makes a relation with active starformation implausible. We cannot still rule out that the maser in NGC 4051 is associated with starforming activity on the basis of high-resolution observations with pc-scale resolution. However, we favor the idea that AGN activity gives rise to the H_2O maser in the galaxy since NGC 4051 contains an AGN and the physical environment could prevent a high-luminosity maser. The H_2O maser in the NLS1 galaxy NGC 5506 shows several narrow (1-2 km s^{-1}) maser lines near the systemic velocity with variable maser flux densities of 0.1-0.3 Jy (Braatz, Wilson & Henkel 1996). The luminosity of such spiky components is on the order of 1 $L_\odot$, which is comparable with those in NGC 4051. The similarity of the NGC 4051 maser to those in NGC 5506 is also evident in the broad variable components (line widths of 20-80 km s^{-1}) near the systemic velocities, which are found in most of the H_2O masers associated with AGN activity. The relative weakness of the masers in both galaxies probably results from the environment surrounding these active nuclei, because narrow optical lines and hard X-rays would correlate with intense H_2O masers (Osterbrock & Pogge 1985). Compton reflection components in the form of neutral iron lines in hard X-ray bands have been detected in both NGC 5506 and NGC 4051 (Matt et al. 2001). This could support the presence of an optically thick neutral layer shrouding the Type 1 Seyfert nucleus and the BLR. The detection of an H_2O maser in an NLS1 would also tell us about unified models of AGN because the H_2O masers may trace the medium that obscures the BLR in Type 1 Seyfert nuclei. A complete sample of NLS1 objects should be searched for new H_2O masers using sensitive telescopes.

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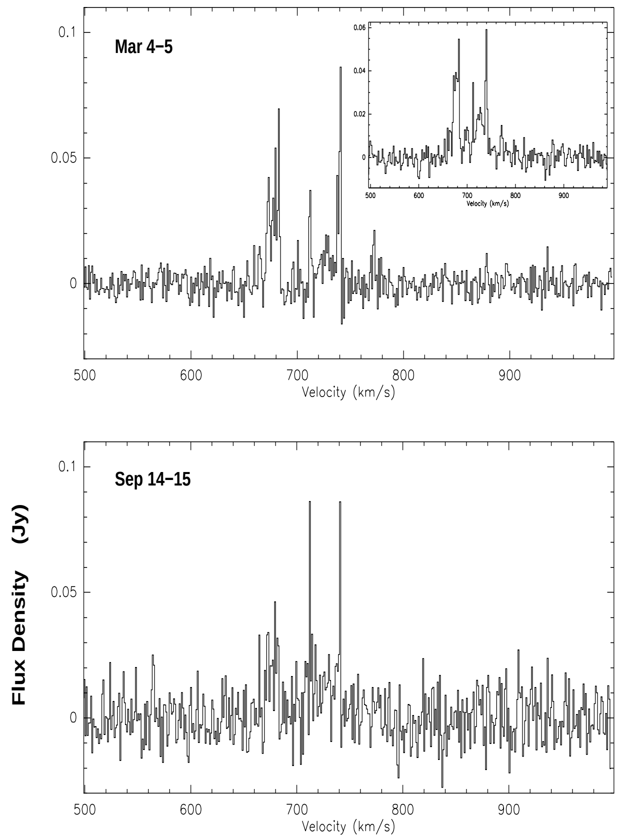

Figure 1. Spectra of the H_2O maser in NGC 4051, obtained with the MPIfR 100 m telescope at two epochs March and September 2002. The velocity resolution is 1.1 km s^{-1}. The adopted systemic velocity of NGC 4051 is $V_{\rm LSR}$ = 730 ± 5 km s^{-1}. The velocities in the spectra are scaled in the radio LSR convention. The spectra were produced by averaging the data taken at two observing days for each epoch. A velocity-smoothed spectrum is displayed as an inset with the resolution of 2.1 km s^{-1}.

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